Mon. Not. R. Astron. Soc. **000**, 1–3 (2001) Printed 1 February 2008 (MN LATEX style file v1.4)

Constraining the window on sterile neutrinos as warm dark matter

Steen H. Hansen (1), Julien Lesgourgues (2), Sergio Pastor (3) and Joseph Silk(1)
(1) Department of Physics, Nuclear & Astrophysics Laboratory, University of Oxford, Keble Road, Oxford OX1 3RH, U.K.
(2) Laboratoire de Physique Théorique LAPTH, B.P. 110, F-74941, Annecy-le-Vieux Cedex, France
(3) Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, D-80805, Munich, Germany

Draft version 1 February 2008

ABSTRACT
Sterile neutrinos may be one of the best Warm Dark Matter candidates we have today. Both lower and upper bounds on the mass of the sterile neutrino come from astronomical observations. We show that the proper inclusion of the neutrino momentum distribution reduces the allowed region to be 2.6 keV $< m <$ 5 keV for the simplest models. A search for a spectral line with $E = m/2$ is thus more interesting than ever before.

Key words: Cosmology: dark matter, early Universe, large-scale structure of Universe

1 INTRODUCTION

Astrophysics provides an increasing amount of independent indications that the dark matter of the universe is warm, so that the small-scale fluctuations are damped out by free streaming. This is most easily achieved by giving a keV mass to the DM particle, in which case the preferred candidate is the sterile neutrino. Support for warm dark matter (WDM) comes from simulations of the number of satellite galaxies (Colin, Avila-Reese & Valenzuela 2000) and of disk galaxy formation without the need for stellar feedback (Sommer-Larsen & Dolgov 2000), which both find that a DM particle mass of about 1 keV is optimal: a significantly larger mass has little impact on galaxy formation, and a significantly smaller mass would lead to the well known difficulties faced by hot dark matter. A quantitative lower limit on the candidate WDM particle mass is inferred from the existence of a massive black hole at large redshift (Barkana, Haiman & Ostriker 2001) and the requirement of sufficiently early galaxy formation to account for reionization of the universe and the observed Ly-α forest properties (Narayanan et al. 2000), constraining the DM mass to be larger than 0.75 keV. A recent discussion of x-ray emission from decays of sterile neutrinos (Abazajian, Fuller & Tucker 2001) has imposed an upper limit of about 5 keV on the neutrino mass. Here we discuss a reinterpretation of these bounds on neutrino mass, and demonstrate that the proper inclusion of the neutrino momentum, arising from the specific production temperature, reduces the allowed sterile neutrino WDM mass to be in the range 2.6 keV $< m <$ 5 keV.

2 WDM PARTICLE DECOUPLING

All of these studies (Colin et al. 2000; Sommer-Larsen & Dolgov 2000; Barkana et al. 2001; Narayanan et al. 2000) are based on the mass-dependent cut-off on small scales, produced by free-streaming. In the previously cited studies, a "conventional" WDM model was considered for the underlying particle physics (see Bode, Ostriker & Turok (2001) and Sommer-Larsen & Dolgov (2000) for recent overviews of such particle models). In such conventional WDM models, the particles decouple in the early Universe at higher temperatures than do massless neutrinos. Therefore they do not share the entropy release from the successive particle annihilations. Since they were relativistic at decoupling, their distribution function in momentum space is subsequently that of a massless fermion, but with a temperature, T_W, which is given today by

$$T_{W_0} = T_{\nu_0} \left(\Omega_W h^2 \, \frac{94\,\mathrm{eV}}{m_W} \right)^{1/3} , \qquad (1)$$

where $T_{\nu_0} \approx 1.946$ K, $H_0 = 100\,h\mathrm{km\,s^{-1}Mpc^{-1}}$, Ω_W is the present energy density of WDM in units of the critical density, and m_W is the WDM mass. The needed entropy release in these conventional models is much bigger than allowed in the standard model, and such WDM candidates should therefore have decoupled before a larger gauge group breaks down.

Now a very natural candidate for the WDM particle is a massive sterile neutrino mixed with an ordinary neutrino (Dodelson & Widrow 1994; Colombi, Dodelson & Widrow 1996; Shi & Fuller 1999; Dolgov & Hansen 2001; Abazajian, Fuller & Patel 2001). Since the mixing angle is temperature dependent (Nötzold & Raffelt 1988) (and for small vacuum

mixing angle, $\sin^2 2\theta \sim 10^{-7}$), only a small amount of these heavy neutrinos, relative to ordinary active neutrinos, can be produced at high temperatures. The distribution function of sterile neutrinos is, to a fair approximation, characterized by the temperature of massless neutrinos, but smaller by a factor $\mathcal{X}$. For a specific choice of m_W and Ω_W today the value of $\mathcal{X}$ can be found from

$$\mathcal{X} = \Omega_W h^2 \left(\frac{94\,\mathrm{eV}}{m_W}\right) \sim 10^{-2}\,, \tag{2}$$

therefore the two models produce the same contribution to ρ_{tot} of WDM particles today if

$$\mathcal{X} = \left(\frac{T_{W_0}}{T_{\nu_0}}\right)^3 . \tag{3}$$

However, WDM particles with m_W have a *different* distribution function in these two models, and their free-streaming effect is not equivalent. The effect on large scale structure was first discussed in detail by Colombi et al. (1996). We will use conventional WDM (cWDM) when referring to the first case, and sterile neutrino WDM (sWDM) for the second one.

3 LOWER BOUNDS

The two neutrino models are easily included in a Boltzman code, in order to compute the present matter power spectrum $P(k)$. Using the code *cmbfast* (Seljak & Zaldarriaga 1996), we have found analytical fits for the transfer functions, $T(k)$, relating the power spectrum in the WDM to the CDM scenario

$$T^2(k) = \frac{P^W(k)}{P^{CDM}(k)} \quad \text{for} \quad \Omega_W = \Omega_{CDM}\,, \tag{4}$$

where P^W is the power spectrum for cWDM, and a similar expression with $P^\nu(k)$ for the sWDM model. These transfer functions, which essentially reflect the free streaming cut-off, have the form

$$T(k) = \left[1 + (\alpha k)^{2\nu}\right]^{-5/\nu}\,, \tag{5}$$

where k is the wavenumber in units $h\mathrm{Mpc}^{-1}$, $\nu = 1.12$, and α depends on the cosmological parameters as

$$\alpha = A\left(\frac{\Omega_W}{0.3}\right)^b \left(\frac{h}{0.65}\right)^c \left(\frac{m_W}{500\,\mathrm{eV}}\right)^d . \tag{6}$$

Numerically we find for cWDM, $A = 1.07$, $b = 0.11$, $c = 1.20$ and $d = -1.11$ in good agreement with Bode et al. (2001). For the sWDM one can derive similar numbers by noting that the mass in the cWDM case differs by (T_{W0}/T_{ν_0}). This means that if we have a dependence $\Omega_W^b h^c m_W^d$ for the sWDM case in eq. (6), and a dependence $\Omega_W^{b'} h^{c'} m_W^{d'}$ for the cWDM case, then one finds

$$\Omega_W^b h^c m_W^d = \Omega_W^{b'-d'/3} h^{c'-2d'/3} m_W^{d'+d'/3}\,, \tag{7}$$

which is solved by $b' = b + d/4$, $d' = 3d/4$ and $c' = c + d/2$, in good agreement with what we found numerically, by explicitly changing the massive neutrino phase-space distribution function as done by Lesgourgues & Pastor (1999). To be very explicit, this means that for a given cut-off scale of the power spectrum one can find the corresponding mass of the elementary particle, and the mass will differ in the two cases. E.g. if for cWDM one finds $m_W = 0.75$ keV, then this corresponds in the sWDM case to $m_W = (\Omega_W h^2\, 94\mathrm{eV}/0.75\mathrm{keV})^{-1/3} \cdot 0.75\mathrm{keV} \approx 2.6$ keV, when using $h = 0.7$ and $\Omega_W = 0.4$. In other words, if one believes that sterile neutrinos indeed constitute the dark matter, and they are produced as described in (Dodelson & Widrow 1994; Colombi, Dodelson & Widrow 1996; Dolgov & Hansen 2001; Abazajian, Fuller & Patel 2001), then the bounds obtained by Barkana et al. (2001) and Narayanan et al. (2000), $m_W > 0.75\,\mathrm{keV}$, should really be multiplied by a factor 3.4, and the *lower* bound on sterile neutrinos as dark matter is thus about 2.6 keV.

This lower bound may be subject to minor corrections. First, the temperature of the sterile neutrinos is really slightly lower than the active neutrino temperature, since the sterile neutrinos are being produced while the muons are still present in the Universe, $T \approx 130$ MeV (Langacker 1989; Kainulainen 1990; Barbieri & Dolgov 1990, 1991). Similarly, for the neutrino states being produced above the QCD phase transition, one must also take into account the quark degrees of freedom (Abazajian et al. 2001a). Another effect arises from the fact that the produced sterile neutrino spectrum is not exactly thermal, but slightly warmer in the sense that the higher momentum part is more populated than the lower momentum part (Dolgov & Hansen 2001; Abazajian et al. 2001b). Furthermore, the factor of 3-4 found above depends on the specific values of Ω_W and h, and can therefore change slightly. It is also worth noting, that if the sterile neutrinos are produced resonantly (Shi & Fuller 1999), through a pre-existing lepton asymmetry, then the upper limit on 5 keV may weaken substantially (Abazajian et al. 2001b).

4 UPPER BOUNDS AND DISCUSSION

Sterile neutrinos in the keV mass range have a decay time that is of cosmological interest. Recently a very interesting paper appeared (Abazajian et al. 2001b), where the signature from decaying sterile neutrinos in galaxies and clusters of galaxies was studied in detail ⋆. A bound $m < 5$ keV was derived, using the relation between mass and mixing angle obtained in (Abazajian et al. 2001a). We thus conclude that a sterile neutrino as WDM must lie in the mass range 2.6 keV $< m < 5$ keV, and it is therefore more interesting than ever before to search for a spectral line with energy $E = m/2$ from the decay $\nu_s \to \nu_\alpha + \gamma$.

If future searches for a spectral line from the sterile neutrino decay should give a negative result, then one must find new WDM candidates. An interesting possibility is an active neutrino, which may never reach thermal equilibrium if the reheat temperature at the end of inflation is low enough (Giudice et al. 2001). Such a scenario demands a reheat temperature of a few MeV, and the resulting neutrino distri-

⋆ One could imagine a slight change of strategy in the analysis of (Abazajian et al. 2001b), namely to consider regions with large concentration of dark matter, but with little baryonic matter. Such "dark blobs" may have been observed by inverting the matter distribution in clusters of galaxies from weak lensing, and comparing with the baryonic matter inferred from optical observations of the cluster (Clowe et al. 2000), but the significance of such blobs is far from being established.

bution function is also warmer than a conventional WDM candidate. Such a solution does, however, not appear too natural in view of the recent neutrino data (Ahmad et al. 2001; Toshito et al. 2001), indicating that all the active neutrino masses are sub eV. Several WDM candidates have different bounds from what is presented here, e.g. gravitinos (Pagels & Primack 1982; Borgani, Masiero & Yamaguchi 1996; Kawasaki, Sugiyama & Yanagida 1997) produced in the very early Universe; or sterile neutrinos *if* there should exist an initial lepton asymmetry (Shi & Fuller 1999). Even more traditional DM candidates (like a neutralino) can disguise themselves as WDM, namely if they have scattering cross section with photons or neutrinos. Specifically, for a 100 GeV DM particle with scattering cross section about $\sigma_{DM-\gamma} \approx 10^{-30}\mathrm{cm}^2$ one obtains a reduction of the matter power spectrum corresponding to a conventional WDM candidate with mass about 1 keV (Bœhm et al. 2001).

In conclusion, we have shown that the proper inclusion of the neutrino momentum distribution changes the lower bound allowed for the simplest models of sterile neutrinos as WDM, and the resulting allowed region thus becomes 2.6 keV $< m <$ 5 keV.

ACKNOWLEDGEMENT

It is a pleasure for SHH and SP to thank Kev Abazajian, George Fuller, Kimmo Kainulainen and Dima Semikoz for discussions and comments. SHH and SP are supported by Marie Curie Fellowships of the European Commission under contracts HPMFCT-2000-00607 and HPMFCT-2000-00445. They acknowledge a visit to LAPTH, supported by CNRS, during which part of this work was carried out.

REFERENCES

Abazajian K., Fuller G. M., Patel M., 2001, Phys. Rev. D 64, 023501.
Abazajian K., Fuller G. M., Tucker W. H., 2001, Astrophys. J. 562, 593.
Ahmad Q. R. *et al.* [SNO Collaboration], 2001, Phys. Rev. Lett. 87, 071301
Barbieri R., Dolgov A., 1990, Phys. Lett. B237, 440.
Barbieri R., Dolgov A., 1991, Nucl. Phys. B349, 743.
Barkana R., Haiman Z., Ostriker J. P., 2001, Astrophys. J. 558, 482 [astro-ph/0102304].
Bode P., Ostriker J. P., Turok N., 2001, Astrophys. J. 556, 93.
Borgani S., Masiero A., Yamaguchi M., 1996, Phys.Lett. B386, 189.
Bœhm C., Riazuelo R., Hansen S. H., Schaeffer R., 2002, preprint astro-ph/0112522.
Clowe D., Luppino G., Kaiser N., Gioia I., 2000, Astrophys. J. 539, 540.
Colin P., Avila-Reese V., Valenzuela O., 2000, Astrophys. J. 542, 622.
Colombi S., Dodelson S., Widrow L. M., 1996, Astrophys. J. 458, 1.
Dodelson S., Widrow L. M., 1994, Phys. Rev. Lett. 72, 17.
Dolgov A. D., Hansen S. H., 2002, Astropart. Phys. 16, 339.
Giudice G. F., Kolb E. W., Riotto A., Semikoz D. V., Tkachev I. I., 2001, Phys. Rev. D 64, 043512.
Kainulainen K., 1990, Phys. Lett. B 244, 191.
Kawasaki M., Sugiyama N., Yanagida T., 1997, Mod.Phys.Lett. A12, 1275.
Langacker P., 1989, UPR-0401T.
Lesgourgues J., Pastor S., 1999, Phys. Rev. D 60, 103521.
Narayanan V., Spergel D. N., Ma C.-P., Davé R., 2000, Astrophys. J. 543, L103.
Nötzold D., Raffelt G., 1988, Nucl. Phys. B307, 924.
Pagels H., Primack J. R., 1982, Phys.Rev.Lett., 48, 233.
Seljak U., Zaldarriaga M., 1996, Astrophys. J. 469, 437.
Shi X., Fuller G. M., 1999, Phys. Rev. Lett. 82, 2832.
Sommer-Larsen J., Dolgov A. D., 2001, Astrophys. J. 551, 608.
Toshito T. [SuperKamiokande Collaboration], 2001, preprint hep-ex/0105023